

# INTERSTELLAR SCINTILLATION AS THE ORIGIN OF RAPID RADIO VARIABILITY IN THE QUASAR J1819+3845.

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Quasars shine brightly due to the liberation of gravitational energy as matter falls onto a supermassive black hole in the centre of a galaxy[1]. Variations in the radiation received from active galactic nuclei (AGN) are studied at all wavelengths, revealing the tiny dimensions of the region and the processes of fuelling the black hole. Some AGN are variable at optical and shorter wavelengths, and display radio outbursts over years and decades[2]. These AGN often also show faster variations at radio wavelengths (intraday variability, IDV)[3, 4] which have been the subject of much debate[5]. The simplest explanation, supported by a correlation in some sources between the optical (intrinsic) and faster radio variations[6, 7], is that the rapid radio variations are intrinsic. However, this explanation implies physically difficult brightness temperatures, suggesting that the variations may be due to scattering of the incident radiation in the interstellar medium of our Galaxy[8, 9]. Here we present results which show unambiguously that the variations in one extreme case[10] are due to interstellar scintillation. We also measure the transverse velocity of the scattering material, revealing a surprising high velocity plasma close to the Solar System.

The most extremely variable extragalactic source known at radio wavelengths is the quasar J1819+3845. This quasar shows variations of factors of 4 or more on a timescale of hours, easiest interpreted as scintillation due to scattering in the interstellar medium (ISM)[10]. One can think of this scattering medium as focusing and defocusing the waves from the source, producing a pattern of dark and bright patches[11]. As we move through these patches, or scintles, we observe a temporal variation in intensity. In order to display this effect, the source must be small: J1819+3845 is only tens of microarcseconds (a few light-months at the source redshift 0.54)[10].

As the Earth moves through the scintillation pattern, two telescopes At different locations should see a difference in the observed time of the intensity

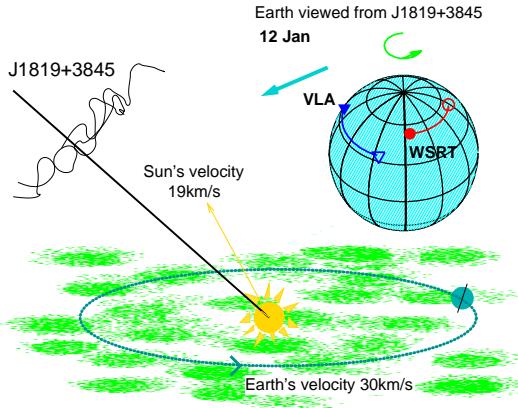


Figure 1: Sketch illustrating the scintles projected onto the solar system. The inset shows the Earth and its projected velocity w.r.t. LSR (blue arrow) as seen from J1819+3845. Filled and open symbols show the telescopes at start and end of the observation run respectively. As the Earth rotates, the value of the ‘delay’ in arrival of intensity extrema will change during the observation due to the changing orientation of the baseline between the telescopes with respect to the vector velocity of the scintillation pattern. The delay is also dependent on the time of year (due to the Earth’s movement around the Sun) and the relative motion of the Solar System and the scattering plasma.

maxima and minima (fig.1). A similar technique was used by Rickett & Lang[12] who used the decorrelation of signals between telescopes to put limits on the size and apparent velocity of the scintles from a pulsar and by Jauncey et al[13] for the other known intra-hour variable PKS 0405-387[14]. Compared to other IDV sources, or even PKS 0405-387, the rapidity and depth of the variations in J1819+3845 make it the perfect candidate for measurement of this delay.

The observations were conducted simultaneously with the NRAO Very Large Array (VLA) in New Mexico, and the Westerbork Synthesis Radio Telescope (WSRT) in the Netherlands. The source showed large, rapid variations on both days (fig. 2). We see that there is a difference in the time at which the earliest peaks reach the telescopes (WSRT leads VLA). We also see that at the end of the observations this delay has reversed, such that the VLA leads WSRT. This delay, and reversal, is repeated on both days. If the scattering plasma is stationary with respect to the Local Standard of Rest,

the predicted time lag from the motion of the Earth and Sun alone is  $\sim$  200 secs, with the signal arriving at the VLA first throughout the run. This clearly cannot account for the observations, so we used the observations to solve for the velocity of the scattering plasma w.r.t. the LSR, transverse to the line of sight.

From a minimization of the total squared flux density difference we calculate the projected plasma velocity. We obtain for 7 Jan 2001:  $v_{RA} = -32.8 \pm 0.5$ ,  $v_{Dec} = 14.3 \pm 3$  km/s and for 12 Jan 2001:  $v_{RA} = -32.2 \pm 0.5$ ,  $v_{Dec} = 16.1 \pm 1$  km/s. It can be seen that we find very good agreement between the results obtained from observations of both days. This shows that to first order the assumption of a temporally 'frozen' scintillation pattern is justified. Combining these we calculate the plasma velocity to be  $v_{RA} = -32.5 \pm 0.5$ ,  $v_{Dec} = 15.5 \pm 1$  km/s (i.e. the plasma moves West and North). We also fitted a single time delay to  $\sim 15$  minutes of data around the largest maxima, normalising the two lightcurves over the time of interest to the same mean flux density. Solutions which pass through these values are consistent with the results quoted above. We plot both these results and the delays fitted as described above in fig. 3. We can constrain the plasma velocity so well because at these values the predicted delay changes very rapidly with changes in plasma velocity. The existence of many maxima and minima in our data is important as it removes the possibility of the delay, and the calculated plasma velocity, being an artefact of flux calibration errors.

We have previously suggested[15] a velocity of the plasma screen in order to explain the change in timescale of the variations over a year, but this was not a measurement as here, but an interpretation of the data, and the velocity was very poorly constrained. For comparison the preliminary result presented in [15],  $v_{RA}=3$  km/s,  $v_{Dec}=25$  km/s predicts a very different delay: from around +60 sec at the beginning of the observations to around +150 sec at the end. We will present a combination of both these analyses in a forthcoming paper.

We point out that we are measuring the transverse velocity of the local plasma: in general, radial velocities are measured (via spectroscopic techniques). Also note that whereas scintillation observations of pulsars are significantly affected by their own transverse velocities (up to several hundred km/s), the effect of a transverse velocity of (jet features in) AGNs even as high as the speed of light is reduced to a fraction of a km/sec by the distances involved.

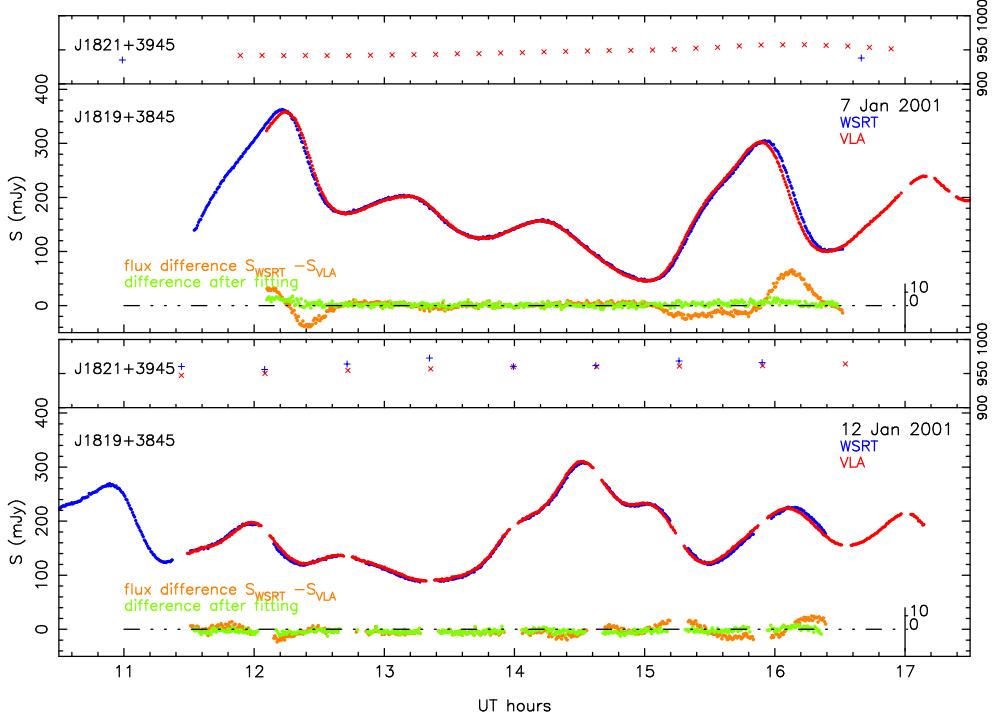


Figure 2: Results of VLA and WSRT observations from 7 and 12 January 2001. Data were averaged over 30 sec. The time difference in the arrival of the signals can be seen as a horizontal separation of the blue and red lines. The vertical axis of the difference signal before and after fitting has been expanded by a factor of 2.5. A total of 11 VLA antenna were used for the observations described here. The central frequency at both telescopes was 4875 MHz, and the bandwidths similar (80 and 100 MHz). VLA observations of a nearby calibrator source (J1821+3945) are shown in the top panel of each plot. Slightly different observing strategies were used on each run. On 7 January 2001 we observed the source continuously, with a sub-set of antennae observing the calibrator. On 12 January 2001 we used the same antennae to nod between the source and the calibrator, observing the latter for 3 minutes every  $\sim 35$  minutes. On both dates the observations described above were bracketed with observations of the calibrator and a flux density calibrator (3C 286). Elevation (and other time dependent) gain variations at the VLA were determined using the calibrator J1821+3945 were found to be up to 3%. The data was corrected for these effects (see below). Observations in good weather at WSRT typically yield 1% flux density reliability. This is applicable to all but the first hour of the 7 January 2001 run, when light rain caused an estimated extra 1-2% extinction. The error we quote on the result is obtained using a number of different determinations of the absolute flux density scale, and acceptable changes throughout the run, including: no temporal changes in gain corrections, a linear change, and gain corrections determined by observations of the calibrator, which is assumed stable. Thermal noise in 30 sec is 1 mJy (WSRT) and 0.6 mJy (VLA).

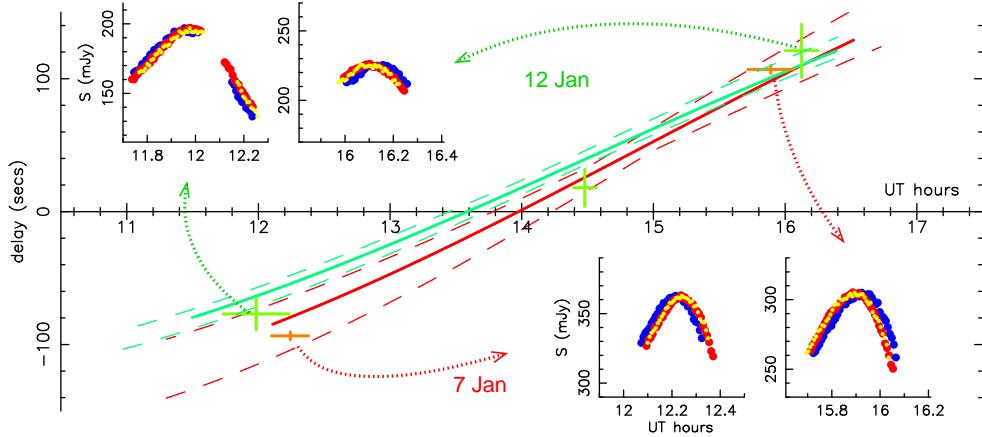


Figure 3: The calculated delays as a function of observing time for both days. The delays are calculated as a function of time from the projected baseline and velocity vector. We use a circular Earth orbit and assume that the Sun is moving at 19.7 km/s towards 18h, 30° (J2000). As the direction of the Sun's motion happens to be only 10° from J1819+3845, errors caused by its uncertainty are negligible. For a wide range of plasma velocities we calculated the total squared flux density difference, after time shifting the data according to the calculated delay. Minimizing this quantity gives the plasma velocity. The associated delays are plotted as the diagonal lines. The results from a given calibration scheme produce errors of less than 1 km/sec, but the final error is dominated by calibration uncertainty. The error we quote is that obtained using a number of different determinations of the absolute flux density scale, and acceptable changes throughout the run. In addition, independent fits to portions of the data are shown with  $3\sigma$  error bars. The data from times with large delays are shown in the insets (red and dark blue as before, yellow showing the WSRT data after fitting).

The determination of a peculiar velocity argues that the scattering structure is discrete. This measurement of the transverse velocity of the ionised scattering material cannot be directly compared to radial velocity measurements of HI, but we note that there is no anomalous feature known in this direction[16]. A nearby pulsar J1813+4013 has an unremarkable dispersion and rotation measures ( $42 \text{ cm}^{-3}\text{pc}$  and  $47 \text{ rad m}^{-2}$ )[17], although the medium in front of J1819+3845 may not extend to this line of sight. We have previously estimated[10] that this scattering region is located at around 20 pc from the Sun. The scatterer may be related to the Local Bubble[18], and if so, for the reasons given above, is more likely to be a discrete structure at the boundary than due to the putative intervening hot gas.

A small difference in the flux densities observed at the two telescopes (after delay correction) as the telescopes pass through different regions of the scintles is expected. The size of the scintles in the direction of motion is  $\sim 4000 \text{ sec} \times 25 \text{ km/sec} = 10^5 \text{ km}$ . If the scintles were of similar size perpendicular to this, we can estimate the expected difference in the intensities on a typical baseline of 6000 km by considering the flux density differences between the two curves if they are shifted  $6000/10^5 \times 4000 = 240 \text{ sec}$ . This gives a potential 5-10% flux density difference (after delay correction) between the two curves. However, differences are less than 2% on both days (fig.2), suggesting the scintillation pattern is highly anisotropic, in agreement with preliminary analysis of the variation of the timescale over a year[15].

To account for these observations there must be an unusually high fraction of turbulent electrons, if the electron density is that of the typical extended ISM. In comparison to the conditions found in highly turbulent, ionised regions, e.g. around OB stars[19, 20, 21] however, the required conditions are very modest. Interestingly, the A0 star  $\alpha$  Lyrae (Vega), which at 8 pc is within the estimated distance range for the screen, is at a projected angular separation of J1819+3845 of  $3^\circ$ , which is only 0.4 pc. Whether the origin of the turbulent plasma could be related to mass loss from this star, or a feature of the so-called Local Fluff[22], remains to be investigated.

Our observations prove beyond doubt that the variations in J1819+3845, the most extreme example of an IDV source, are due to scintillation. Yet, as this source must be extremely small, it could easily be intrinsically variable on time scales of a few months (using simple light-travel time arguments). Using relativistic outflow arguments its is not difficult to bring this down to weeks. Intrinsic variations on these time scales would be very hard to separate from

scintillation induced variations. We have evidence however that the source is remarkably stable over a period of many months with only a slow increase in brightness over the last two years (Dennett-Thorpe & de Bruyn, in prep). Scintillation in known variable sources and those with slower variations will be more difficult to prove directly. However, the few percent variations seen on day scales in many IDV[23] is likely to be due to scattering of structures of tens of microarcseconds through more typical ISM[24]. This implies that most AGN have brightness temperatures no higher than  $10^{12} - 10^{14}$ K, not  $10^{17} - 10^{20}$ K, as would otherwise be required. Perhaps the most serious argument against an intrinsic explanation of the IDV phenomenon, which requires extremely small angular sizes, now becomes how to avoid scintillation induced variations dominating all the observed variability.

The lack of correlation of strength or timescale of variations with frequency or galactic latitude is sometimes cited as evidence against ISS as cause for IDV[25]. However as the variations are affected by the intrinsic size of the source, the location and motion of the effective scatterer as well as the season of the observations, such correlations may easily be washed out. Although the annual modulation in the variations of B0917+62 have been explained in terms of scintillation through the general Galactic ISM[26, 27], J1819+3845 demonstrates that one cannot assume that the scattering effectively occurs throughout this medium. It is important to note that the scattering of resolved AGN will be weighted by the material closer to the observer.

The delay in arrival times of the intensity variations at two widely separated radio telescopes is a neat proof that a propagation effect causes the extreme variations in this one quasar. The small size of the quasar J1819+3845 is probably related to the unusual rising radio spectrum. The absence of many sources which scintillate in this manner is presumably due to a combination of an unusually small, stable source, and an atypically strong, close scatterer. We nonetheless expect that more similarly extreme IDVs will be discovered.

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